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Image deblurring using lensless Fourier transform holography

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IMAGE DEBLURRING USING
LENSLESS FOURIER TRANSFORM HOLOGRAPHY

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Bachelor of Science in the
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ABSTRACT

Using lensless Fourier transform holography the problem of deblurring an out-of-focus image on a photographic transparency was studied. First a lensless Fourier transform hologram of an out-of-focus image was taken using a point reference source. By replacing this hologram into the recording plane and re-illuminating it with coherent light, the imaging wave transmitted through the hologram immediately gives, by Fourier transformation, the restored, deblurred image. A bar target was photographed out-of-focus, and using this method, with subjective analysis at 95% confidence, the deblurred image was judged better than the original. This method of image deblurring does indeed work, but the restoration process is limited by the amount the transparency was out-of-focus to begin with.

ACKNOWLEDGEMENTS

I am especially indebted to the Central Intelligence Agency for their funding of this project. Also thanks must go to my associates who endured with me during the trying times of this project. My thanks to John More who came through at the last minute to supply me with the needed film. Typing of the manuscript was ably handled by Ms. Shirley McCoy.

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INTRODUCTION

Since the first introduction of the basic concepts of the hologram and the holographic process by Denis Gabor in 1948, there has been an extensive devělopment in the techniques associated with the formation of the hologram, the materials used for recording the hologram, and the suggested application of the various techniques. A hologram is the record of an interference pattern formed between a field of interest and a known or reproducible background or reference field. When this record, the hologram, is illuminated with a beam equivalent to the reference field, the original field of interest can be recreated. Thus both amplitute and phase of the field of interest are stored and recreated, compared to a photograph where only the amplitude is stored.

The modern phase of holography started early in the 1960's with the implementation of the off-axis reference beam method (Leith and Upatnieks 1962). This was closely followed by the use of the gas laser in holography, which clearly allowed for considerable versatility in the experimental implementation and thus holograms could be made in reflected light leading to the so-called "three dimensional photography." High resolution techniques were discussed (Stroke and Falconer 1964) as a prelude to optical holography microscopy. In a very defferent direction of development, the pulsed ruby laser was used in holographic recording (Silverman 1964), and the concepts of far-field holography developed (Thompson and Parrent 1964) and used for one of the first direct applications of holography-that of particle size analysis. It must also be mentioned that the use of hologram as an optical filtering element in coherent optical processing was the first conceived and implemented by VanderLugt (1964).

The basic concept of holography is quite simple once it has been stated. The hologram is the recorded interference pattern between a field of interest and a known background or reference field. Let the complex amplitude of the field of interest be $A_1(x)$ given by

$$A_1(x) = a_1(x) \exp (i\phi_1(x)), \tag{1}$$

where $a_1(x)$ is the amplitude and $\phi_1(x)$ is the phase. If this field is recorded alone then the resultant intensity $I_1(x)$ is given by

$$I_1(x) = A_1(x)A_1^* = a_1(x)^{\;2} , \tag{2}$$

where the star denotes a complex conjugate. The phase portion of the complex field is completely lost. However, if before recroding this field, a second known field, $a_2(x)\exp(i\phi_2(x))$, coherent with the first is added to it, then the resultant intensity is given by

$$\begin{aligned} I_r(x) = a_1^2(x) + a_2^2(x) = \big[& a_1(x)a_2(x) \\ & (\exp i(\phi_1(x) - \phi_2(x)) + \\ & \exp -i(\phi_1(x) - \phi_2(x))\big] \end{aligned} \tag{3}$$

The last term in equation (3) simplifies to give $2a_1(x)a_2(x)\cos(\phi_1(x))$. The hologram is now illuminated with the reference field and the resultant field, $A_h(x)$ propagating from the hologram is

$$A_h(x) + a_2(x)\exp(i\phi)2(x)\Big[a_1^2(x) + a_2^2(x)$$
$$+a_1(x)a_2(x)\Big\{\exp\ i(\phi_1(x) - \phi_z(x)) +$$
$$\exp\ -i(\phi_1(x) - \phi_2(x)\Big\}\Big] \qquad (4)$$

The two terms of interest in this equation are the last two; the first of these represents a component that is in the original field of interest multiplied by the intensity associated with the reference field. (If $a_2(x)$ is a constant, then this term is exactly the original field.) The second of these terms involves a field that is the complex conjugate of the original field of interest. These two terms represent two propagating waves, the first of which creates the effect of the original wave being present.[1]

The nature of the two fields that produce the hologram will be dependent upon the specific geometry of the system used.

Fourier transform holography is the method of producing holograms which generate at the hologram plane wave amplitudes which are either exact Fourier transform of the subject or the Fourier transform multiplied by a slowly varying phase factor. For this to happen, the reference source must effectively lie in the same input plane as the subject. As a consequence, the analysis is intended to apply strictly to planar subjects (e.g. transparencies) and is less applicable as the subject extends out of the input plane. We require the subject to be illuminated with a plane wave, and a lens following the input plane operates on light from both the subject and reference source.

A Fourier transform hologram is a hologram which records the interference of two waves whose complex amplitudes at the hologram are the Fourier transforms of both the subject and reference source.

The Fourier transform of a two-dimensional subject can be displayed in the back focal plane of a lens by Fraunhoffer diffraction.[2] An arrangement for forming Fourier transform holograms in the matter of VanderLugt is shown in Figure 1. If $s(x,y)$ is the transmittance of the transparency in the front focal plane of the lens illuminated by a plane wave, the subject amplitude at the hologram located in the back focal plane is $S(\xi,\eta)$ where $s(x,y) \supset S(\xi,\eta)$. Also located in the front focal plane is a point source $\delta(x - b,y)$ whose transform, a plane wave amplitude given by $\exp(-2\pi i\xi b)$, acts as the reference wave and illuminates the back focal plane along with $S(\xi,\eta)$. The intensity of the interference pattern formed by the two transforms is

$$\begin{aligned} I &= \exp(-2\pi i\xi b) + S(\xi,\eta) \exp(2\pi i\xi b) \\ &+ S^*(\xi,\eta) = 1 + \left|S(\xi,\eta)^2\right| + \\ &S(\xi,\eta) \exp(2\pi i\xi b) + S^*(\xi,\eta) \\ &\exp(-2\pi i\xi b) \end{aligned} \tag{5}$$

We assume the developed hologram has a transmittance $t(x,y) \propto I$. If the hologram is illuminated with a plane wave propagating along with the z axis with constant amplitude r_0, the product $r_0 t(x,y)$ represents the complex amplitude A of the diffracted light just behind the hologram, where

$$A \propto r_0 t(x,y) \propto I = 1 + S^2 + S\exp(2\pi i \xi b) + S^*\exp-(2\pi i \xi b). \tag{6}$$

Once the hologram is recorded, a lens placed immediately after the hologram, Figure 2, will display in its back focal plane the product of the inverse Fourier transform of A and a sperical phase factor. If we detect only the intensity in the backfocal plane then we can neglect the spherical phase factor. The zero order terms in Equation (6) will be focused about the origin of that plane. The inverse Fourier transform of the third term on the right of Equation (6), s(x-b, y) is the original transmittance shifted b units from the origin in the positive x direction while the transform of the fourth term yields $s^*\left[-(x+b, -y)\right]$, the conjugate of the original transmittance, inverted and shifted b units from the origin in the negative x direction. The diffracted light converges to a real image formed in a common plane. The photograph of the output of the Fourier transform hologram displayed in the back of the focal plane of the reconstructing lens only detects intensity.[3]

When sources other than point sources are used in holography for the reconstruction, the resolution of the image forming process is reduced, because of the spreading or smearing of the image point. The resolution loss enters in the form of a convolution between the object and the image of the source, so that we may say that the image of a point object is spread out to the width of the source image. In the past it had generally been assumed that the use of an extended source in the recording of a hologram would resutl in an irretrievable loss of resolution.

A very important advance was made in holography and in image formation in coherent light when Stroke showed that the loss of resolution which would result from the recording of a hologram with an extended source could, paradoxically be retrieved, in the reconstruction, by illuminating the hologram also with an extended source, provide that the correlation function of the two suitably structured sources had a narrow central peak, of a width comparable to the resolution limit sought in the two-step process.[4]

The type of Fourier transform holography used in this project is lensless Fourier transform holography. In this variety, the lens (L2 in Figure 1) in the hologram-forming arrangement is removed, while the point reference source is maintained in the subject plane. The subject wavefront to be recorded at the hologram plane is now in the near-field or Fresnel diffraction pattern of the sujbect transparency. Since we have Fresnel diffraction, the Fresnel zone plate is in the diffraction pattern of the subject transparency. The zone plate has focusing properties, as it acts as both a positive and a negative lens. With these properties of the system, an out of focus image will be able to be deblurred.

The blurring or coding of the blurred photograph g(x,y) may be expressed as a spatial convolution:

$$g(x',y') = \iint_{-\infty}^{\infty} f(x,y)h(x'-x,y'-y)dxdy \qquad (7)$$

between the desired image $f(x,y)$ and the instrumental impulses response function h(x,y). This equation takes the form of the product

$$\bar{G}(u,v) = \bar{F}(u,v) \quad \bar{H}(u,v) \tag{8}$$

We record the Fourier-transform hologram of g(x,y) by using h(x,y) as the extended reference source Figure (3). The hologram is

$$\begin{aligned} I(u,v) &= (\bar{G} + \bar{H}) \quad (\bar{G} + \bar{H})^* \\ &= \bar{G}^2 + \bar{H}^2 = \overline{GH}^* + \bar{G}^*\bar{H} \end{aligned} \tag{9}$$

and from Equation (8), we may write Equation (9) as

$$I(u,v) = \bar{G}^2 + \bar{H}^2 + \bar{F}\overline{HH}^* \quad = \bar{F}^*\bar{H}^*\bar{H} \tag{10}$$

Because we are considering, in particular, the decoding condition, the case when $\overline{HH}^* = 1$, ($\overline{HH}^* = 1$ when by Fourier transformation, $h \star h^* = \delta$, $\star$ is the spatial autocorrelation) we note that $\overline{FHH}^* = \bar{F}$ since F is nothing more than the Fourier transform of the imaging wave in the focal plane of the lens "looking" trhough the hologram. Accordingly, it is sufficient to replace the hologram into its recording position, and illuminate it with a wave of unit amplitude, as originating from a point source situated 'in place' of the extended source h(x,y) used in the recording, Figure (2).[5] This procedure will yeild a deblurred image.

METHODOLOGY

In order for the holographic process to be successful, any vibrations must be eliminated from the system in order to preserve the high frequency interference fringes. A sturdy optical table which rested on two inner tubes served that purpose in this experiment.

The holographic set up is shown in Figure 1. The laser, a 5 mw Helium-Neon gas laser, (λ = 632.8nm) is deflected by a mirror (m1) through the shutter to the cube beam splitter. The transmitted beam passes through to a 43x microscope objective, which acts as the reference point source. A 10 μm pinhole was originally used, but the low intensity of the beam coming out was too low. This reference point source is then focused onto the holographic plate. The reflected beam gets reflected again (m2) so the two beams are parallel. The reflected beam then gets spatially filtered and collimated and goes to illiminate the subject transparency onto the holographic plate. With this system combined with the holographic film used (Holotest, Agfa) an exposure of 1/60 seconds was needed. At this fast shutter speed, the shutter introduced vibrations, thus wiping out the interference fringes. To get rid of this problem, a 1.5 N.D. Filter was placed in front of the shutter in order to increase the exposure time to 4 seconds, where the slight vibration caused by the shutter was not a factor.

A series of negatives, (Pan-X) were taken with a f:1.4 Minolta lens at f/1.4. An in focus negative was taken to be used as a reference. The negatives were taken at a distance of 1.5 meters from the bar target. The next negative was taken with the focusing aperture set at 3 meters while the last negative was set at infinity. These negatives were processed in D-76 for 8.5 minutes at 70° F. These negatives were then contact printed to HD-Com, (DuPont, High Density Computer Output Microfilm) developed in Recron, 90° F at 90 seconds. This gives an overall gamma of -2 for the system, this way transmittance is proportional to exposure so the photographic system provides a linear mapping of irradiance into transmittance provided exposures are restricted to the linear portion of the characteristic curve.

It is with these transparencies the deblurred images were made by putting the transparency into the plane wave and making the hologram (D-19, 7 minute 4 second exposure). A beam intensity ratio of 4:1 was used. Because of the noise that is associated with the point source, being a microscope objective and not spatially filtered the hologram had a lot of noise in it and was very uneven exposed. By putting a glass diffuser in front of the reference beam, the image was greatly cleaned up. This hologram is now put into the subject plane and its hologram was then taken. This second hologram when viewed in white light is the deblurred image. This method was used for both out-of-focus images.

The reference negative, both out-of-focus negatives and their deblurred counterparts were all printed up (Figure 4, 5, 6) to be used for subjective analysis.

The Rickmers-Todd method for analysis subjective judgements was used. Twelve judges rated each print in the paired-comparison method. Of the twelve judges, ten had no triads, i.e. were consistant in their criteria for judging quality, and their data was used. Next, testing for inconsistency among judges having no triads, at a confidence level of 95%, there was agreement of the judges. A measure of the amount of agreement is the coefficient of concordance, where 0 is no agreement and 1 is total agreement, in this case it was 0.84. Ranking the prints with 95% confidence, the partially blurred deblurred print was ranked higher than the original blurred print, as was also the case for totally blurred deblurred image which also was ranked higher than the original out-of-focus image.

SUMMARY AND CONCLUSIONS

With a 5% chance of error the deblurred images looked better than their out-of-focus origionals, even though a glass diffuser was put in front of the reference source, therefore losing some resolution of the system. The degree of sharpness obtained still depends upon the equipment (i.e. point reference source) and also the amount of out-of-focus of the transparency. Even though the deblurred images were better than their origionals neither one came close in rank to the reference print. The totally deblur was better than its origional but not as good as the partially blurred image. The final ranking of the prints, with 5% chance of error in judgement:

1) Reference print
2) Partial blurred - deblur
3) Partial blurred - original
4) Totally blur - deblur
5) Totally blur - original

therefore I would conclude that, with a 5% chance of error that this method of image deblurring using lensless Fourier transform holography does indeed deblur.

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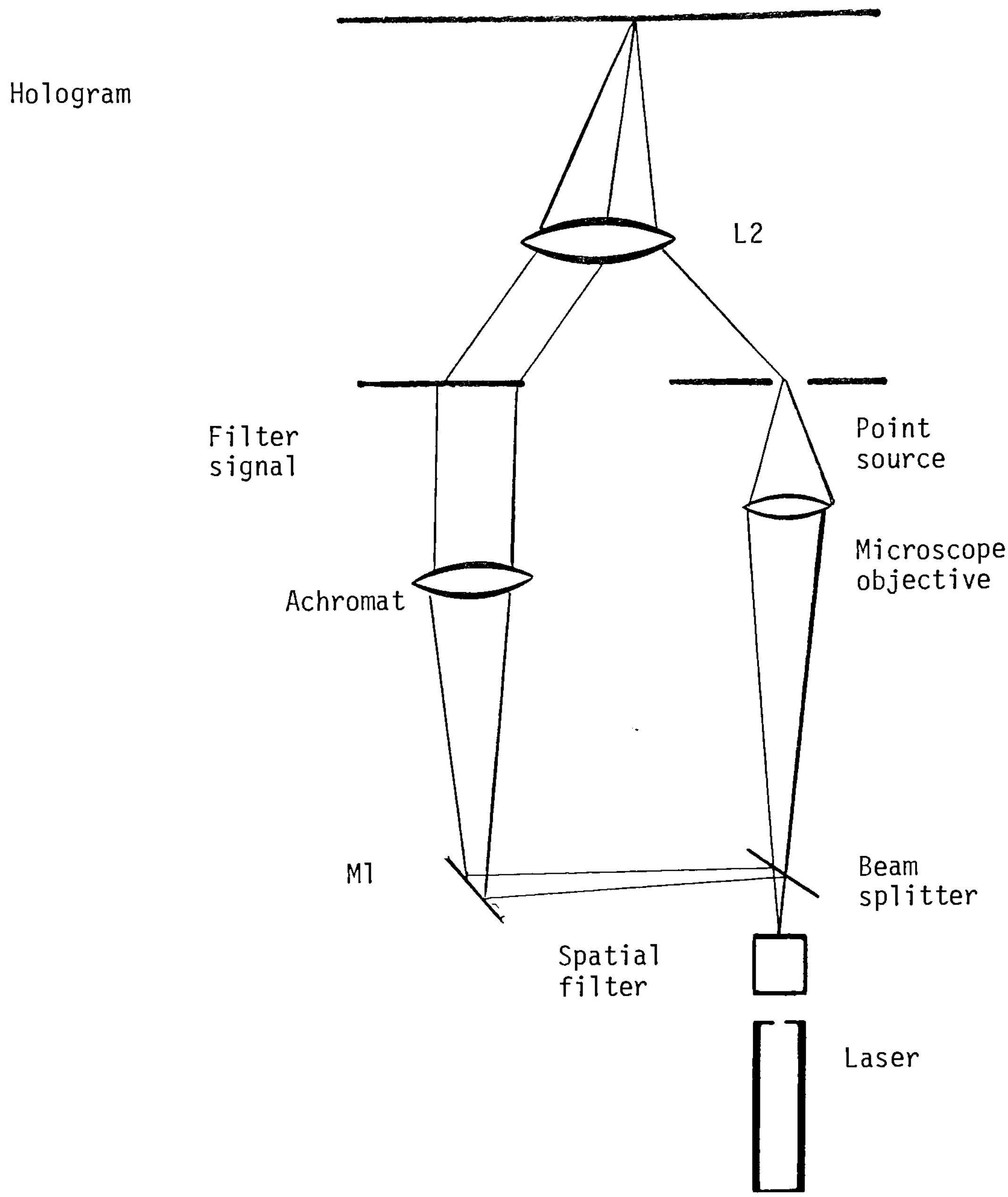
APPENDIX

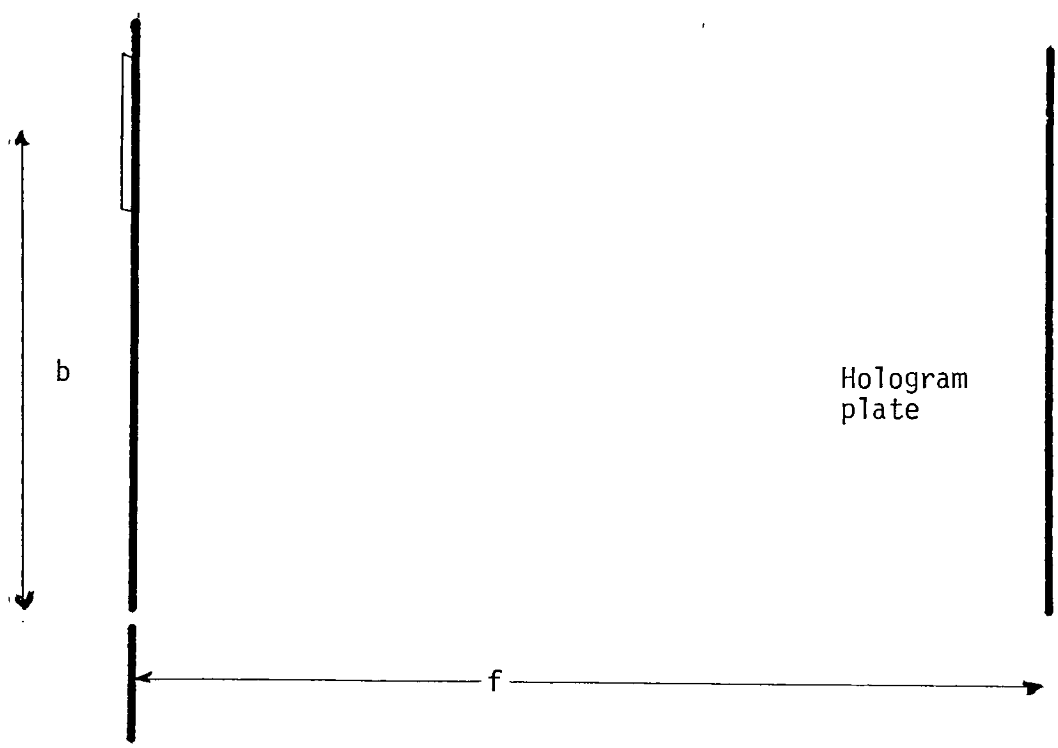
Figure 1



Set up for Fourier transform holography

Figure 2

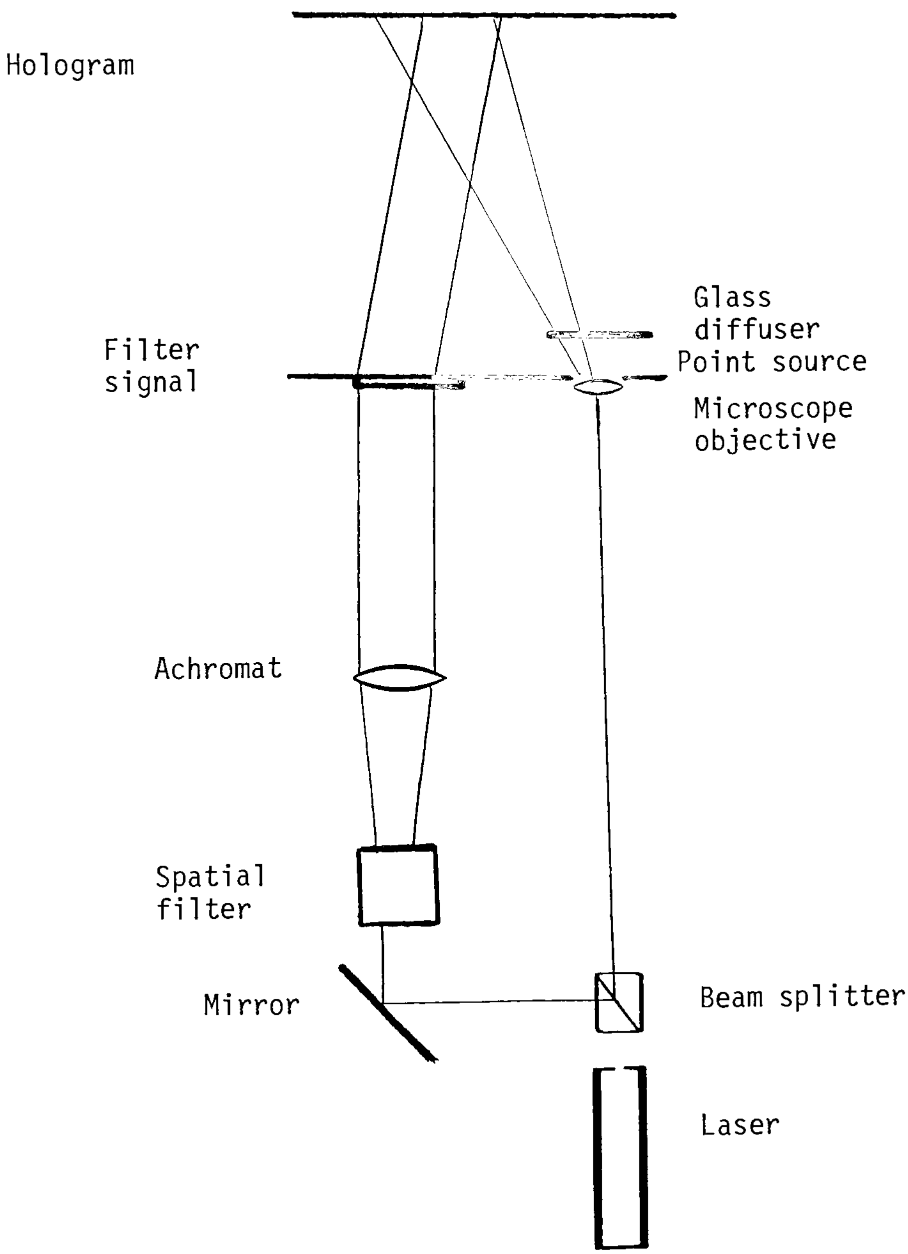
Extended source T_o (ξ-b)



Object T_o (ξ)

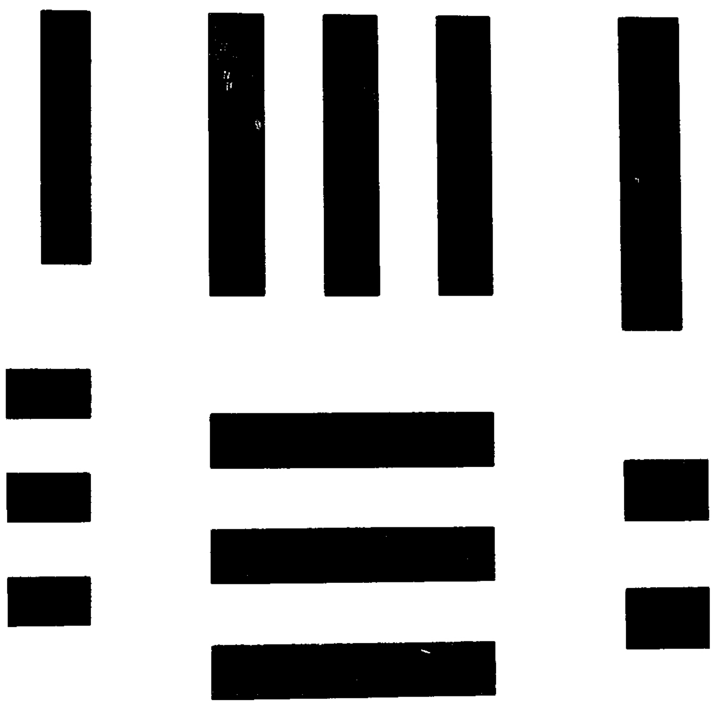
Extended source holography

Figure 3



Lensless Fourier transform holography

Figure 4

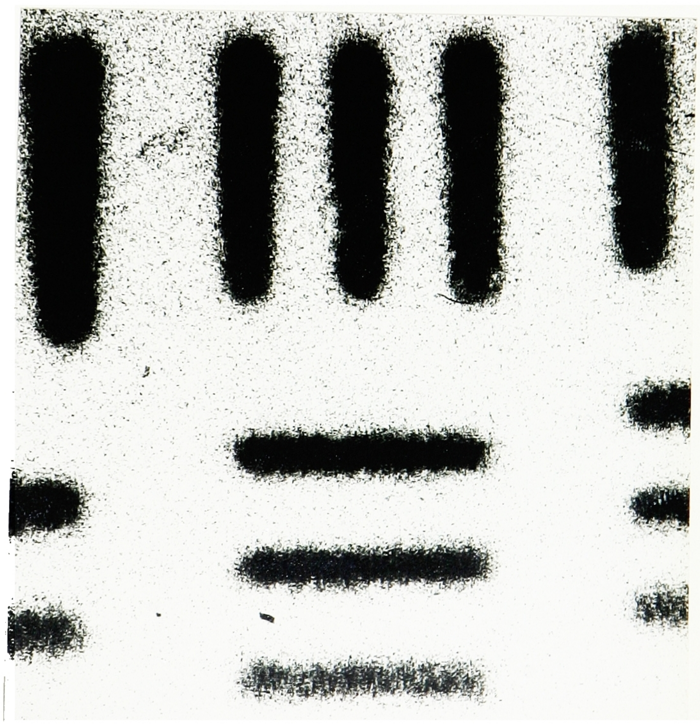


The in focus image

Figure 5

Partially blurred image

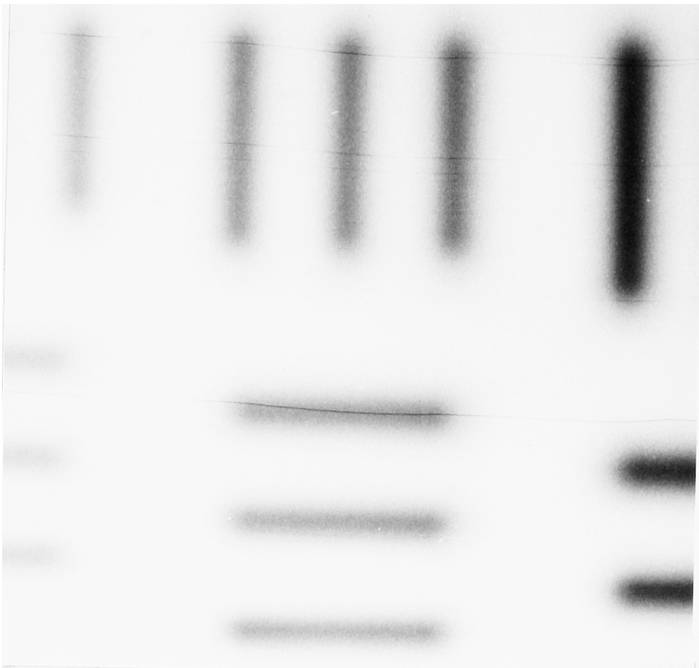
A) Original



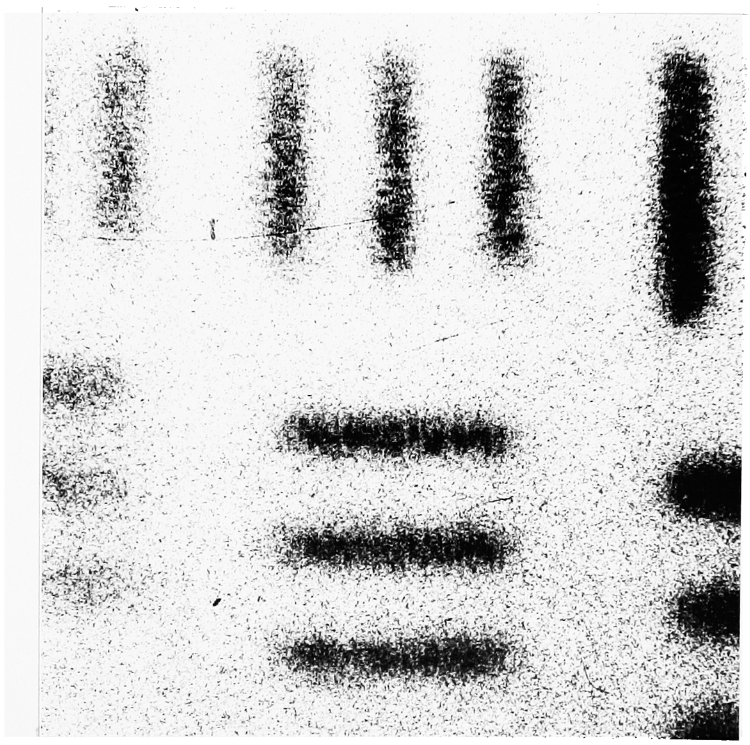
B) Deblurred image

Figure 6

Totally blurred image



A) Original



B) Deblurred image